Although a significant amount of work has been performed on many parts of this system or similar systems, very little has been done from a life cycle viewpoint. For example, earlier studies have assessed the energy used at the biomass plantation, but did not include upstream operations such as raw material extraction or equipment manufacture (see section 11.0). Moreover, processes required for biomass production have not formerly been integrated with transportation and electricity production for the purpose of identifying major emissions beyond CO_2. Unlike previous efforts, this study serves to pull together all major operations involved in producing electricity from biomass, while identifying a large number of possible stressors on the environment.

Generally, a life cycle assessment is conducted on two competing processes. Such a comparative analysis highlights the environmental benefits and drawbacks of one process over the other. In keeping with the primary purpose of this study, to better define the environmental aspects of this process irrespective of any competing process, a comparative analysis was not performed. Future work, however, will seek to answer the question of how this process measures up environmentally against other renewable and fossil-based systems.

Frequently, others perform life cycle assessments in order to respond to criticism about the environmental effects of a product or to address a limited number of possible consequences. In doing so, only data that are required to address the goals of the project while keeping the scope of the assessment reasonable are included. In conducting this life cycle assessment, every effort was made to include all correct and best available data. Since the primary goal of this work is to identify sources of environmental concern and to discover possible design improvements to mitigate these concerns, it is our intention to report all possible environmental impacts of the process. Unfortunately, because no biomass-based IGCC plants are currently operating, it will be difficult to validate some of the assumptions used in this study for some time. The system being assessed is conceptual, and represents only what an integrated power facility using biomass grown as a dedicated feedstock might look like. However, emissions from the power plant itself may be verifiable from tests on the demonstration facility now being constructed in Burlington, Vermont. Additionally, biomass test plots will continue to provide more accurate information on required feedstock production operations and what environmental effects are likely. This study will be regularly updated as real operating data become available.

2.0 Methodology

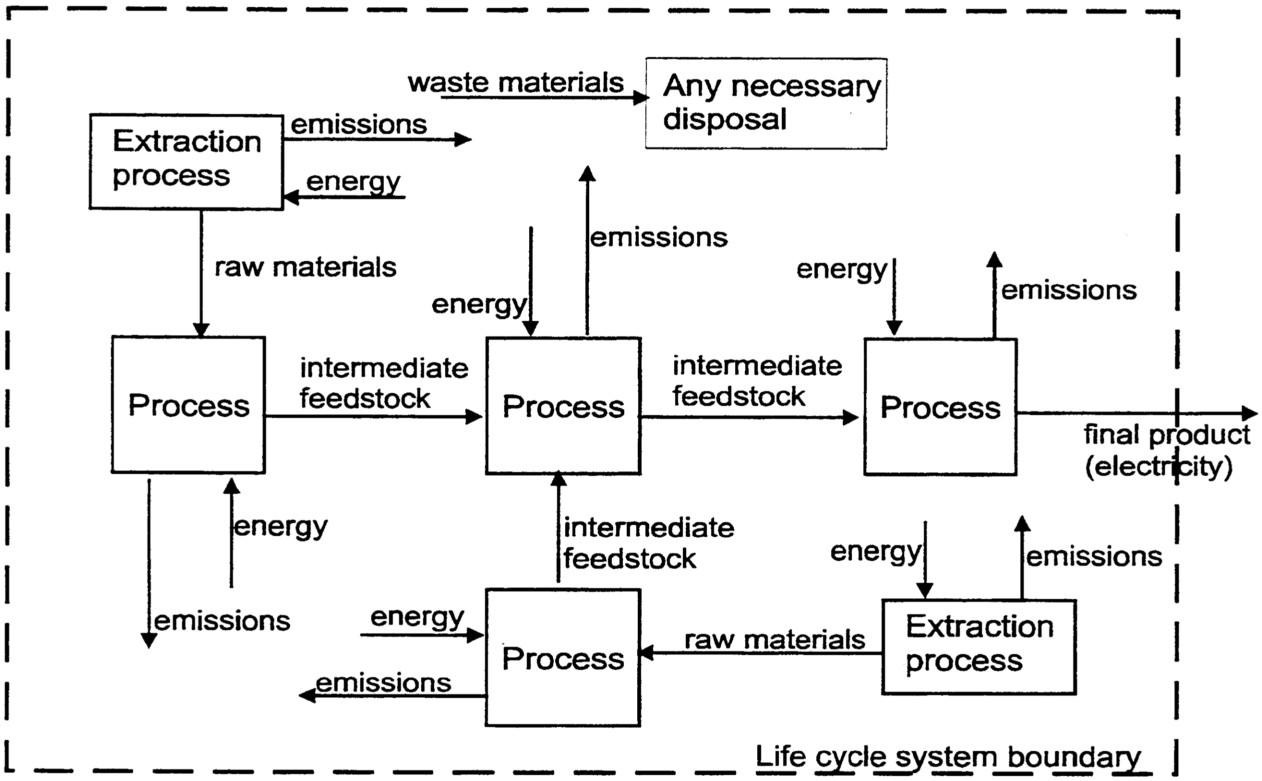
In the United States, the Society of Environmental Toxicology and Chemistry (SETAC) has been actively working to advance the methodology of life cycle assessment through workshops and publications. From their work, a three-component model for life cycle assessment has been developed (SETAC, 1991), and is considered to be the best overarching guide for conducting such analyses. The three components are inventory, impact analysis, and improvement. The inventory stage involves quantifying the energy and material requirements, air and water emissions, and solid waste from all stages in the life of a product or process. The second element, impact assessment, examines the environmental and human health effects associated with the loadings quantified in the inventory stage. The final component is an improvement assessment in which means to reduce the environmental burden of a process are proposed and implemented. It should be emphasized that life cycle assessments are not necessarily performed step-wise and that they are dynamic rather than static. For example, process improvements may become obvious during the inventory assessment phase, and altering the process design will necessitate a reevaluation of the inventory. Additionally, depending on the purpose of the LCA, an impact assessment may not be necessary. Most importantly, a life cycle assessment needs to be evaluated periodically to take into account new data and experiences gained. To date, most work in life cycle assessment has focused on inventory, although efforts to advance impact assessment and improvement are significant. The International Organization for Standardization (ISO) is also involved in life cycle assessment development under the new ISO 14000 environmental management standards. Specifically, the Sub-Technical Advisory Group working on this task has made progress in constructing inventory assessment guidelines, but much disagreement remains on the impact and improvement elements.

A detailed inventory was conducted for this study, and is the subject of most of the results presented in this report. Additionally, some very simple design changes were made to the power plant, and recommendations for further process improvements are made. Methodology development for performing impact assessments is in its infancy and felt to have limited value for achieving the goals of this work. Therefore, only a cursory examination of the environmental effects was performed. This consisted of placing each stressor (e.g., CO_2, coal consumption) into an impact category (e.g., greenhouse gas, resource depletion, etc.). It is important to note that even without a full impact analysis, recommendations for process improvements can be made by identifying major sources of environmental stressors.

2.1 System Boundaries and Data Availability

The system boundaries for any life cycle assessment should be drawn as broadly as possible. In addition to counting the material and energy flows of the primary process of interest, those processes involved in the extraction of raw materials and production of intermediate feedstocks must be included. Intermediate feedstocks are sometimes referred to as ancillary materials because they are used indirectly in the manufacture of the final product (e.g., the fertilizer needed to grow biomass). The means of disposing products, by-products, wastes, and process materials are also included within the life cycle boundary. The system concept diagram shown in Figure 2 serves to better describe the meaning of terms such as boundary, process, intermediate feedstock, and materials.

Figure 2: System Concept in Life Cycle Assessment



The question of where to stop tracking the energy and material uses of upstream processes is an important one since the analysis is infinite if boundaries are not drawn to encompass the most important impacts to the environment. Generally speaking, the impacts of upstream processes become less significant the further you get from the process of interest, and a situation of diminishing returns becomes apparent past the third level of upstream processes. Conducting a life cycle assessment can be extremely time consuming, and as part of the scoping process, decisions should be made to determine at which point the results will have limited use. Very often, the determination of system boundaries is made based on data availability, and to a large extent, this is how the present analysis was conducted. Data exist on the extraction of natural resources, processing, manufacture, and delivery to the point of use for most process feedstocks, such as diesel fuel and ammonium nitrate fertilizer. Thus, the assessment included nearly all of the major processes necessary to produce electricity from biomass. Examples of operations that were felt to be too far from the system of interest to be included in the study are the construction of facilities to manufacture transportation equipment, and manufacture of mining equipment. Additionally, because of a complete lack of information, seedling production was not included in the analysis. Perlack *et al* (1992) report that the effects of this step will be negligible on regional and global scales, but could be important locally. Figures 3 and 4 show the processes included in the overall system. The solid lines in these figures represent actual material and energy flows, while the dotted lines indicate

Figure 3: Biomass Production and Transportation Boundaries for Life Cycle Assessment

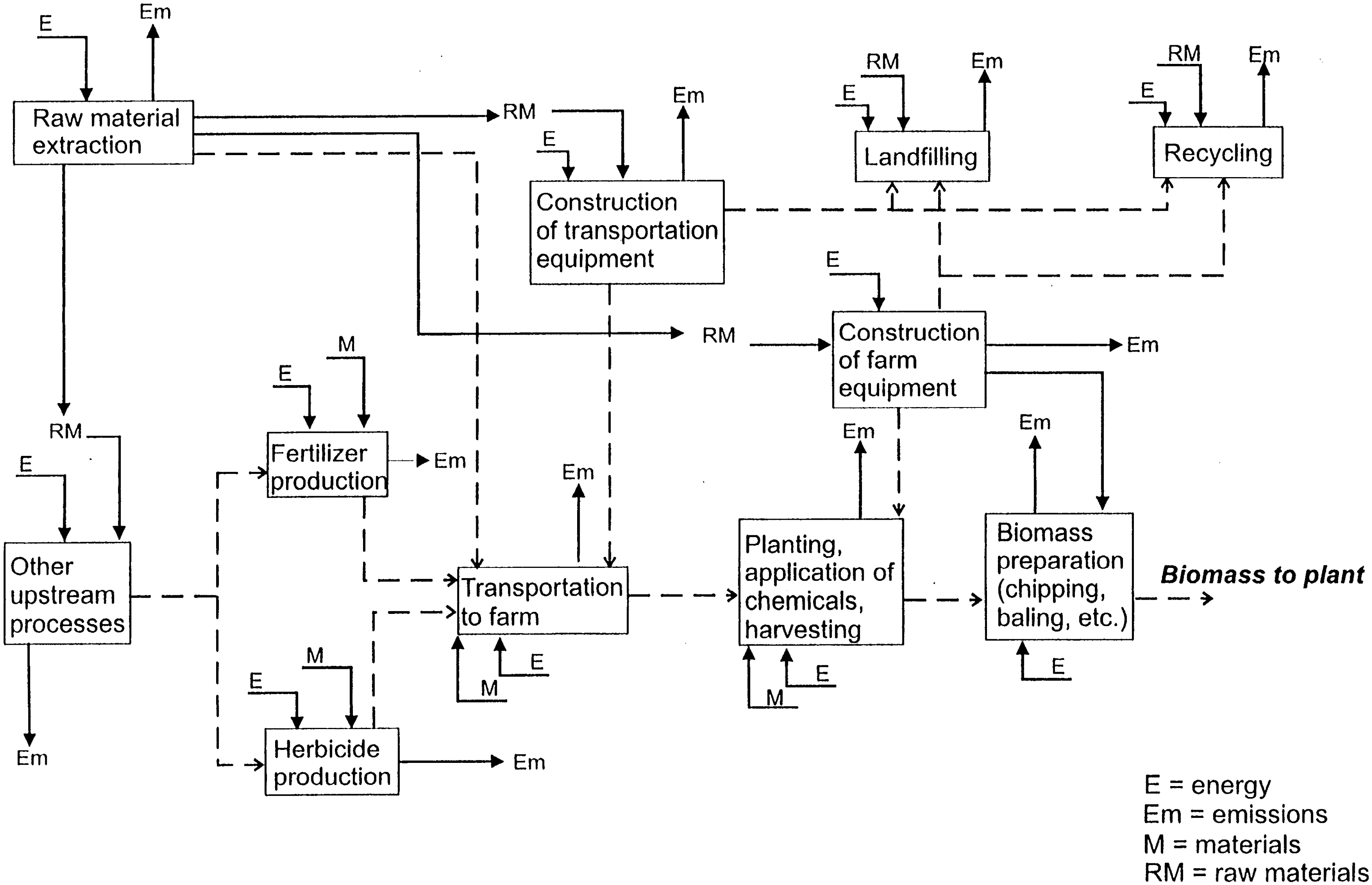
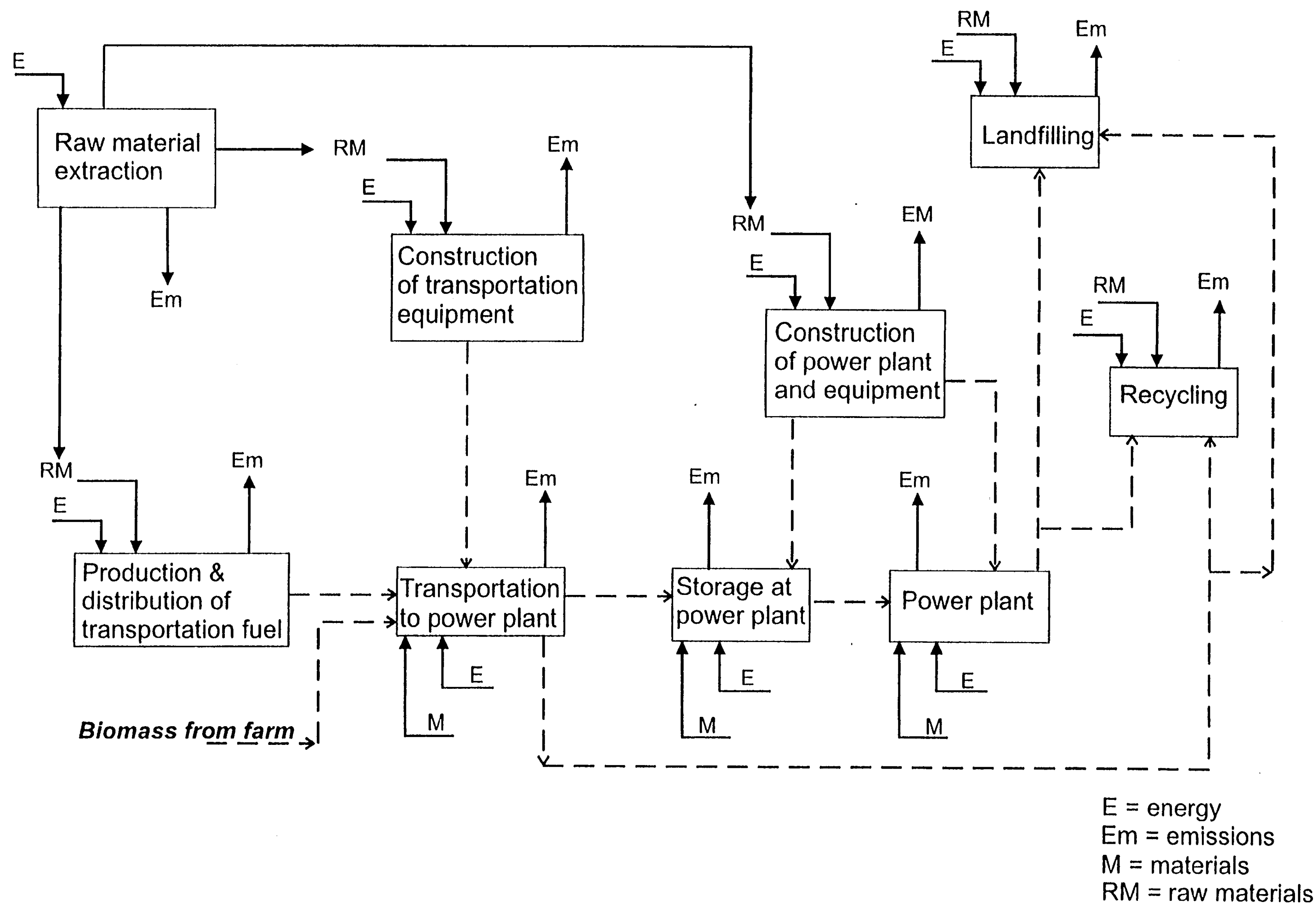


Figure 4: Power Generation and Transportation Boundaries for Life Cycle Assessment



logical connections between process blocks. In Figure 3, "Other upstream processes" refers to major manufacturing steps needed to produce intermediate feedstocks such as ammonia required for ammonium nitrate production.

2.2 Methodology - Energy Considerations

The energy use within the system was tracked so that the net energy production could be assessed. Two types of energy were accounted for: 1) energy used directly in each process block, and 2) energy contained in the materials used in each process block. In the case of a power plant, all energy used in these categories is subtracted from the energy produced as electricity. Examples of the first type of energy consumption include the electricity required to run equipment such as compressors and the fuel used in transportation. The second type of energy, that contained in the raw materials and intermediate feedstocks, is the sum of combustion and process energies; this is sometimes referred to as the embodied energy of a material. The combustion energy is applied where non-renewable fuels are consumed, and is the energy that would be released during combustion of the fuel (i.e., its heating value). This practice reflects the fact that the fuel has a potential energy that is being consumed by the system. The combustion energy of renewable resources, those replenished at a rate equal to or greater than the rate of consumption, was not subtracted from the net energy of the system. This is because, on a life cycle basis, the resource is not being consumed. The second part of embodied energy, process energy, is the total amount of energy consumed in all upstream processes used to bring the raw material or intermediate feedstock to the system in the form in which it is used. To determine the net energy in this LCA, the energy used directly in each block plus the embodied energy of all materials consumed by the system, were subtracted from the energy produced by the power plant.

2.3 Methodology - Comparison with Other Systems

It has already been stated that this analysis was performed only on the biomass system, and not for the immediate comparison with fossil-fueled power options. Additionally, prior land use considerations were not made, and a comparison of biomass crops with other crops was not included. Prior land use will certainly affect many of the variables used in this study. For example, what was grown on the plantation before biomass crops will affect soil carbon sequestration and how much fertilization and tilling are required. Regardless, existing experience with biomass simply does not provide enough parametric data, thus making it necessary to base inputs for this study on the best information available from recent field trials. Additionally, although it would be useful to compare the environmental effects of dedicated energy crops to agriculture crops, lack of data and the desire to stay focused on the main aspects of biomass power require a deferment to later studies.

2.4 Methodology - Sensitivity Analysis

A sensitivity analysis was conducted to determine the parameters that had the largest effects on the results and to minimize the impact of incorrect data on the conclusions. Variables included in the sensitivity analysis were chosen to reflect system areas that had inherently more unknowns in the data. Examples include feedstock yield, fossil fuel use at the plantation, thermal NOx emissions, and power plant operating capacity. Each parameter was changed independently of the others, giving the change in results in relation to only that variable. Therefore, no one single sensitivity case reflects the best-case or worse-case scenarios for this process. It's important to note, however, that upstream material and energy uses affected by a parameter included in the sensitivity analysis, were automatically changed in the model. For example, since fertilizer use is calculated in kg/acre, the total amount of fertilizer applied was automatically increased in the sensitivity case that examined lower biomass productivity.

2.5 Accounting

Keeping track of the large number of material and energy flows to and from the process blocks within the system represents an enormous accounting challenge. Several software packages, designed specifically for life cycle assessment, are available to make this job easier. Many include, as part of their database, processes that are commonly encountered such as the extraction of raw materials or the production of large market chemicals. The software package chosen for this study was Tools for Environmental Analysis and Management (TEAM), by Ecobalance, Inc. Originally developed in France, this software has been adapted to reflect standard energy and chemical processes in the United States. The process blocks within the biomass-based power production system that were available in the TEAM database, known as Data for Environmental Analysis and Management (DEAM) are shown in the following table. Note that this table includes only those process blocks taken from the DEAM database and not all of those in the assessment. Production of raw materials includes extraction, any necessary refining, and transportation to point-of-use. Each of the operations in the table contains the emissions, raw material use, and energy consumption of nearly all upstream processes. For example, ammonia production includes natural gas extraction, reforming, and ammonia synthesis. The data within TEAM were checked against other sources to determine reliability. In general, the data were found to be consistent with those found in the literature. In particular, the energy embodied in fossil fuels and certain commodity chemicals was checked against data in Boustead and Hancock (1979), Fluck (1992), Pimentel (1980), and Cervinka (1980). DEAM databases on the production of fertilizers were found to be consistent with the extensive amount of information found in the literature (see Feedstock Production Literature in the References section at the back of this report).

Table 1: Process Blocks Taken from DEAM

Coal production
Natural gas production
Diesel oil production
Electricity production (U.S. overall and region-specific)
Diesel oil combustion (for truck transport and farm equipment operation)
Light fuel oil production
Light fuel oil combustion
Aluminum production from ore and scrap
Steel production from ore and scrap
Iron production from ore and scrap
Landfilling waste materials
Potash fertilizer production
Phosphate fertilizer production
Nitric acid production
Limestone production

Processes within the system that were not available in DEAM were constructed manually. Data were obtained from the literature and from researchers in biomass production and use, and entered into TEAM. Calculations were then performed using TEAM on the entire system and reported in spreadsheet format. For additional information on how process blocks are connected, the screen printouts from the TEAM software for this analysis are attached as Appendix A. Sufficient data were not available on some novel processes within the system such as gas turbine combustion of biomass-derived synthesis gas and all of the specifics of biomass production. The data used in these areas were taken from research and documented studies. Additionally, data that are site-specific, such as soil erosion and feedstock transportation requirements were based on averages from field studies or best-guess approximations.

The functional unit, also known as the production amount that represents the basis for the analysis, was chosen to be unit of energy produced. Most results are presented per kWh or per MWh of net electricity produced by the power plant. Because the emissions, resources consumed, and energy use are functions of the size of the plant and the technology, care should be taken in scaling results to larger or smaller facilities, or applying them to other biomass systems.

2.6 Time Frame and Issues in Assessing Environmental Consequences

Most life cycle assessments are performed on a plant-life basis. That is, the material and energy flows represent values seen in normal operating years or values averaged as though they are the same each year. However, because the environment experiences the impacts when they actually occur, averaging emissions and resource depletion makes the consequences look better or worse than they really are at any time during system operation. This is especially true in a system using biomass since resource production is initiated several years before plant operation begins, and tapers off in the final years when the plant is still operating at full capacity. Therefore, this study was conducted on a yearly basis, taking into account each emission and resource use in the year it occurs. To obtain this information, a separate inventory of the system was conducted 37 times, once for each year of operation.

The power plant life was set at 30 years. Because biomass is assumed to be grown on seven year rotations, the total operation of the system was 37 years. Year one is that in which the power plant begins to operate. Years negative seven through negative three consist solely of growing the biomass. No special preparation time is allotted for converting the field from its prior use to a biomass plantation. Both biomass production and plant construction take place in the two years before plant start-up (year negative two and negative one). In years one through 29, biomass production and normal plant operation occur, with the number of fields in production decreasing by one per year from seven to zero in year 30 when the power plant is decommissioned. Table 2 more clearly spells out the operations that take place each year. The amount of biomass in production in any year is related to how much has to be supplied to the power plant at the end of the seven year rotation. Thus, because the power plant operates at less than full capacity in years one and 30, only a portion of a full field is in production in years negative seven through negative one and 23 through 29. Although it is likely that biomass production will occur on a continuous basis once several power plants are operating within a reasonable transportation distance, only the operations directly relevant to this plant are included in the analysis.

Table 2: Major Yearly Operations of the Three Subsystems

Year	System Operations		
	Feedstock Production	Transportation	Power Plant
-7	½ of a field in production	None	None
-6	1½ fields in production	None	None
-5	2½ fields in production	None	None
-4	3½ fields in production	None	None
-3	4½ fields in production	None	None
-2	5½ fields in production	Rail car and truck production Transport of power plant equipment	Power plant construction

Year	System Operations		
	Feedstock Production	Transportation	Power Plant
-1	6½ fields in production	Transport of power plant equipment	Power plant construction
1	7 fields in production	Transport ½ of the biomass required for operation of the power plant at 80% capacity	Operation at 50% of 80% of capacity (40% capacity factor)
2-23	7 fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity Truck production and decommissioning of trucks in years 7, 15, and 22	Operation at 80% of capacity
24	6¾ fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
25	5¾ fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
26	4¾ fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
27	3¾ fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
28	2¾ fields in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
29	¾ of a field in production	Transport all of the biomass required for operation of the power plant at 80% capacity	Operation at 80% of capacity
30	Zero fields in production	Transport 75% of the biomass required for operation of the power plant at 80% capacity Decommission trucks and rail car	Operation at 75% of 80% of capacity (60% capacity factor) Decommission power plant

3.0 Technoeconomic Analysis

Generally, a process is analyzed based on what it will cost to build and operate, but environmental issues are clearly taking a more prominent role in project decision making. In order to better marry economic and environmental considerations, a technoeconomic analysis and life cycle assessment were conducted on the same process. An economic analysis previously performed for this biomass gasification combined cycle system was updated and a design change was incorporated to recycle a portion of the dryer exhaust gas to the char combustor in order to reduce the amount of VOCs emitted to the atmosphere. The original economic analysis for which the updated results are summarized below can be found in more detail in Craig and Mann (1996).